REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1998	Final Report 15 Apr 94 - 31 Dec 97

4. TITLE AND SUBTITLE

Simulation Methodology

5. FUNDING NUMBERS

DAAH04-94-G-0021

6. AUTHOR(S)

Peter W. Glynn and Donald L. Iglehart

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)

Stanford University
Stanford, CA 94305

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

ARO 32892.19-MA-SDI

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Our work on simulation methodology begins with the formulation of a model as a stochastic process. We then use the structure of the stochastic process to develop methods for analyzing the output of the simulation. Diagram 1 is a block diagram which details our approach to system simulation. The performance evaluation and reliability analysis of complex engineering systems requires an ability to analyze mathematical models of these systems. Large-scale stochastic models are required to handle various uncertainties present in these systems. Unfortunately, the complexity of most stochastic models of real systems is well beyond our ability to apply classical mathematical analysis. Computer simulation of stochastic systems has become one of the principal alternatives to classical analysis. The main thrust of our research is improving the efficiency of simulation methods and extending their applicability to wider class of stochastic systems. We also carry out research on a variety of stochastic models with the aim of obtaining closed form solutions or approximations.

14. SUBJECT TERMS	15. NUMBER IF PAGES
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

SIMULATION METHODOLOGY

by

Peter W. Glynn

and

Donald L. Iglehart

FINAL REPORT

August 1998

Prepared under the Auspices

of

US Army Research Contract
DAAH04-94-G-0021

DEPARTMENT OF ENGINEERING-ECONOMIC
SYSTEMS AND OPERATIONS RESEARCH
STANFORD UNIVERSITY
STANFORD, CA 94305

1. INTRODUCTION

This contract covered the period April 15, 1994 through December 31, 1997. It supported Professor Peter W. Glynn for two months in the summer and Professor Donald L. Iglehart for one month in the summer.

Our work on simulation methodology begins with the formulation of a model as a stochastic process. We then use the structure of the stochastic process to develop methods for analyzing the output of the simulation. Diagram 1 is a block diagram which details our approach to system simulation. The performance evaluation and reliability analysis of complex engineering systems requires an ability to analyze mathematical models of these systems. Large-scale stochastic models are required to handle various uncertainties present in these systems. Unfortunately, the complexity of most stochastic models of real systems is well beyond our ability to apply classical mathematical analysis. Computer simulation of stochastic systems has become one of the principal alternatives to classical analysis. The main thrust of our research is improving the efficiency of simulation methods and extending their applicability to wider class of stochastic systems. We also carry out research on a variety of stochastic models with the aim of obtaining closed form solutions or approximations.

2. IMPORTANT RESULTS OBTAINED

High speed communications networks of the future are expected to use the asynchronous transfer mode (ATM) protocol to simultaneously carry data, voice, and video traffic. This traffic flows into a switch which is modeled as a single serve in a queueing network. The design and control of such networks involves the appropriate sizing of buffers used to store message packets. The asymptotic decay rate for the tail of the steady-state waiting time distribution has been derived. This decay rate may be used to create effective bandwidths for admission control and other network resource allocation problems. These rates can also be used to speed up simulations of the network. Steady-state performance measures for highly dependable systems (such as fault-tolerant computer systems) are estimated by simulations involving rare events. Earlier work dealt with Markovian systems that could be formulated as regenerative processes. Our current work assumes that repair and failure times are non-exponential and this leads to non-Markovian systems for which the regenerative structure is lost. A new approach has been developed using importance sampling applied to a sequence of cycles which are no longer independent, identically distributed as in the regenerative case. Experimental results show that the method is effective in practice. Techniques have been developed for estimating the gradient of performance measures with respect to design parameters. These gradient estimates are required for sensitivity analyses and system optimization. System simulations are a natural candidate for parallel processing. A simple way to exploit the power of parallel processing is to run multiple independent replications in parallel and average the results. Whether estimating transient or steady-state quantities, a number of problems arise that can lead to incorrect estimates. We have developed a number of techniques for overcoming these problems. Solutions of Poisson's equation provide the key to studying the bias and variability of additive functionals of a Markov

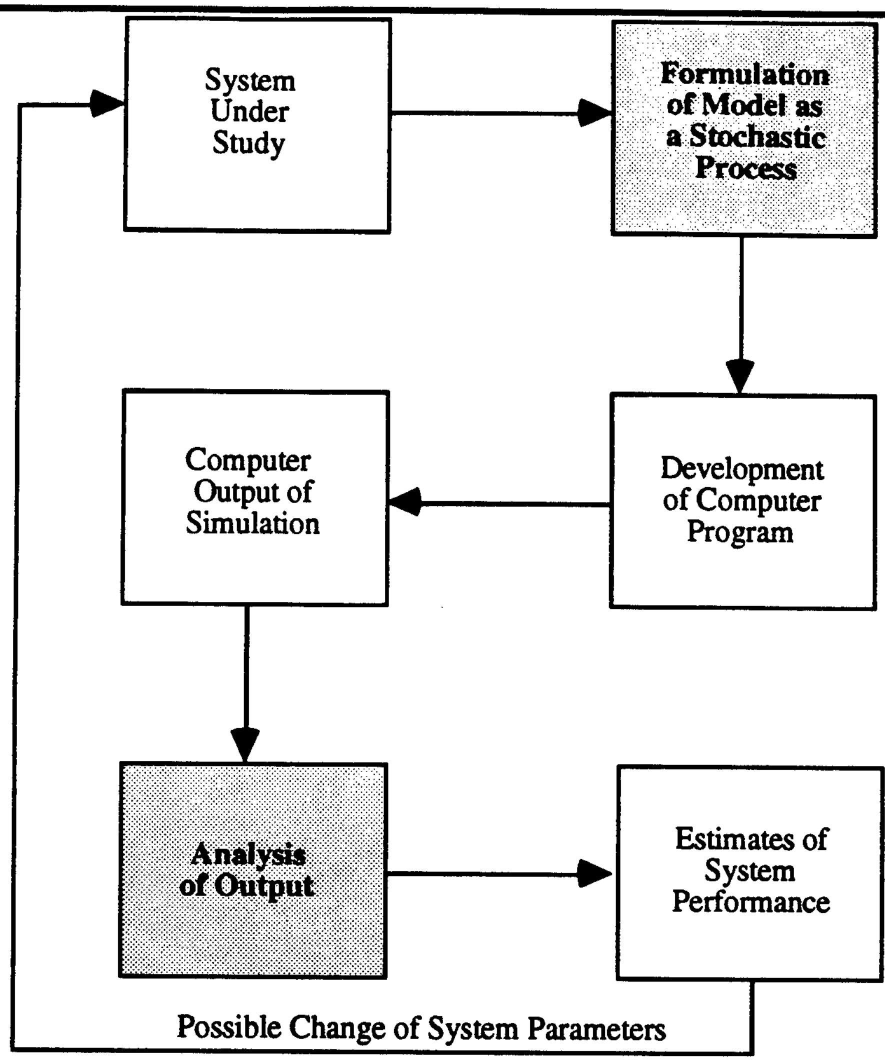

Diagram 1. Technical Approach to System Simulation*
*Our emphasis is on the shaded boxes

chain. These solutions have been obtained for discrete and continuous time Markov chains, and for the waiting time sequence of the single server queue.

The maximum of a random walk over the non-negative integers is an important random variable that arises in insurance risk theory, sequential analysis, and queueing theory. We developed a method for simulating the exact distribution of this maximum along with several ways to reduce the variance of our estimator. In manufacturing environments one is often concerned with optimizing the performance of a system over a set of decision parameters, when the performance can only be evaluated through simulation. We study how fast the number of simulation replications must grow as the number of gird points in the decision space increases. For non-irreducible, general state space Markov chains we developed a criteria for guaranteeing tightness of the chains. Tightness is a condition that guarantees that Markov chains are well behaved in the limit as time becomes large. The shortest processing times scheduling rule is shown to be asymptotically optimal when processing times are exchangeable across machines and independent across jobs. In steady-state simulations estimating the time-average variance constant (TAVC) is critical for obtaining confidence intervals of performance measures. Several methods for estimating the TAVC have been developed in the literature. We have studied the computational complexity of these estimates for the various methods. A continuous time Markov process is governing by its infinitesimal generator. An important problem when observing financial time series is to estimate this generator when the process is only observable at random times. We developed a family of generalized method-of-moment estimators for this problem, the maximum-likelihood estimator being a special case. We established strong consistency, asymptotic normality, and characterization of the standard errors for these estimators.

3. PUBLICATIONS

1. Glynn, P.W., M. Nakayama and A. Goyal. Likelihood Ratio Sensitivity Analysis for Markovian Models of Highly Dependable Systems. *Operations Research* 42 (1994) 137-157.

2. Glynn, P.W. Importance Sampling for Markov Chains: Asymptotics for the Variance. *Stochastic Models* 10 (1994) 701-717.

3. Glynn, P.W. and W. Whitt. Logarithmic Asymptotics for Steady-State Tail Probabilities in a Single-Server Queue. *Advances in Applied Probability* (1994) 131-156.

4. Glynn, P.W., P. L'Ecuyer and N. Giroux. Stochastic Optimization by Simulation: Numerical Experiments with the M/M/1 Queue in Steady-State. *Management Science* 40 (1994) 1245-1261.

5. Glynn, P.W. and P. L'Ecuyer. Stochastic Optimization by Simulation: Convergence Proofs for the GI/G/1 Queue in Steady-State. *Management Science* 40 (1994) 1562-1578.

6. Glynn, P.W.. Efficiency Improvement Techniques. *The Annals of Operations Research* 53 (1994) 175-198.

7. Glynn, P.W. and P. L'Ecuyer. On the Existence and Estimation of Performance Measure Derivatives for Stochastic Recursions 11th International Conference on Analysis and Optimization of Systems, Lecture Notes in Control and Information Sciences 199 (Springer-Verlag) (1994) 429-442.

8. Glynn, P.W.. Poisson's Equation for the Recurrent M/G/1 Queue. *Advances in Applied Probability* 26 (1994) 1044-1062.

9. Glynn, P.W.. Some Topics in Regenerative Steady-State Simulation. *Acta Applicandae Mathematicae* 34 (1994) 225-236.

10. Glynn, P.W., J. Calvin and S. Andradottir. Increasing the Frequency of Regeneration for Markov Processes. *Proceedings of the 1994 Winter Simulation Conference* (1994) 320-323.

11. Glynn, P.W. and T.J. DiCiccio. On the Value of Function Evaluation Location Information in Monte Carlo Simulation. *Management Science* 41 (1995) 733-737.

12. Glynn, P.W. and D.L. Iglehart. A Martingale Approach to Regenerative Simulation. *Probability in the Engineering and Informational Sciences* 9 (1995) 123-131.

13. Glynn, P.W. and D.L. Iglehart. Trading Securities Using Trailing Stops *Management Science* 41, No. 6, (1995) 1096-1106.

14. Glynn, P.W. and W. Whitt. Large Deviations Behavior of Counting Processes and Their Inverses *Queueing Systems: Theory and Application* 17 (1994) 107-128.

15. Glynn, P.W, S. Andradottir and J.M. Calvin. Accelerated Regeneration for Markov Chain Simulations. *Probability in the Engineering and Informational Sciences* 9 (1995) 497-523.

16. Glynn, P.W. Two Approaches to the Initial Transient Problem. *Monte Carlo and Quasi-Monte Carlo Methods in Scientific Computing*. Lecture Notes in Statistics, vol. 106, (1995) Springer-Verlag, New York, 49-57.

17. Glynn, P.W. and H. Damerdji. Performance Analysis of Future Event Sets. *Proceedings of the 1995 Winter Simulation Conference* (1995) 316-321.

18. Glynn, P.W.. Some New Results on the Initial Transient Problem. *Proceedings of the 1995 Winter Simulation Conference* (1995) 165-170.

19. Glynn, P.W. and M.J. Torres. A Set of Extensions to the SIMAN/ARENA Simulation Environment *Proceedings of the 1995 Winter Simulation Conference* (1995) 285-293.

20. Glynn, P.W and S. Meyn. A Lyapunov Bound for Solutions of Poisson's Equation. *The Annals of Probability* (1996) 916-931.

21. Glynn, P.W and J. Glynn. A Diffusion Approximation for a Network of Reservoirs with Power Law Release Rule. *Stochastic Hydrology and Hydraulics* Vol. 10, No. 1, (1996) 17-37.

22. Glynn, P.W and D. Duffie. Efficient Monte Carlo Simulation of Security Prices. *The Annals of Applied Probability*, Vol. 5, No. 4, (1995) 897-905.

23. Glynn, P.W., S. Asmussen and J. Pitman. Discretization Error in Simulation of One-dimensional Reflecting Brownian Motion. *The Annals of Applied Probability*, Vol. 5, No. 4, (1995) 875-896.

24. Glynn, P.W. and W. Whitt. Heavy-Traffic Extreme-Value Limits for Quesues. *Operations Research Letters* 18 (1995) 107-111.

25. Glynn, P.W. and E.W. Wong. Efficient Simulation via Coupling. *Probability in the Engineering and Informational Sciences* 10 (1996) 165-186.

26. Glynn, P.W. and P. L'Ecuyer. Likelihood Ratio Gradient Estimation for Stochastic Recursions. *Advances in Applied Probability* 27 (1995) 1019-1053.

27. Glynn, P.W. Importance Sampling for Monte Carlo Estimation of Quantiles. *Proceedings of the Second International Workshop on Mathematical Methods in Stochastic Simulation and Experimental Design* (1996) 180-185.

28. Glynn, P.W. and K.B. Ensor. Grid-Based Simulation and the Method of Conditional Least Squares *Proceedings of the 1996 Winter Simulation Conference* (1996) 325-331.

29. Glynn, P.W., H. Damerdji, M.K. Nakayama and J.R. Wilson. Selecting the Best System in Transient Simulations with Variances Known *Proceedings of the 1996 Winter Simulation Conference* (1996) 281-286.

30. Glynn, P.W. and J.M. Calvin. Complexity of Non-Adaptive Optimization Algorithms for a Class of Diffusions *Stochastic Models,* Vol. 12, No. 3, (1996) 343-365.

31. Glynn, P.W.. Numerical Computation of Large Deviations Exponents via Simulation. *Proceedings of the 1996 Allerton Conference on Communication, Control, and Computing* (1996) 790-797.

32. Glynn, P.W. and J.M. Calvin.. Average Case Behavior of Random Search for the Maximum. *Journal of Applied Probability*, 34 (1997), 632-642.

33. Glynn, P.W., H. Damerdji and S.G. Henderson. Computational Efficiency Evaluation in Output Analysis. *Proceedings of the 1997 Winter Simulation Conference*, 208-215.

34. Glynn, P.W. and K. Sigman. Independent Sampling of a Stochastic Process. *Stochastic Processes and their Applications* 74 (1998) 151-164.

35. Glynn, P.W. and D.F. Muñoz. A Batch Means Methodology for Estimation of a Nonlinear Function of a Steady- StateMean.

36. Glynn, P.W., W. Nasrallah and R. Levitt. Diversity and Popularity in Organizations and Communities . *Management Science* 43 (1997), 1121-1135.

37. Glynn, P.W., A. Ward, and K. Richardson. Internet Service Performance Failure Detection To appear in *Proceedings of the 1998 Workshop on Internet Server Performance* (Madison, Wisconsin).

38. Glynn, P.W. and H. Damerdji. Limit Theory for Performance Modeling of Future Event Set Algorithms To appear in *Management Science.*

39. Glynn, P.W. and K.B. Ensor. Simulating the Maximum of a Random Walk. To appear in *Journal of Statistical Planning and Inference.*

40.. Glynn, P.W. and W. Whitt. Winning the Hand of the Princess Saralinda. To appear in *Advances in Stochastic Processes*.

41. Glynn, P.W.. The Covariance Function of a Regenerative Process. Accepted by *Stochastic Processes and Their Applications* (pending revisions).

42. Glynn, P.W. and D. Duffie. Estimation of Continuous-Time Markov Processes Sampled at Random Time Intervals. Accepted by *Econometrica.* (pending revisions).

43. Glynn, P.W. and J.M. Calvin. A Family of Regenerative Moment Identities. Submitted to *The Journal of Applied Probability* (1994).

44. Glynn, P.W. and S. Henderson. Derandomizing Variance Estimators Submitted to *Operations Research.*

45. Glynn, P.W. and S. Meyn. Tightness for Non-irreducible Markov. Submitted to *The Journal of Applied Probability.*

46. Glynn, P.W., J.G. Shanthikumar and C.H. Xia. On the Asymptotic Optimality of the SPT Rule for the Static Flow Shop Average Completion Time Problem. Submitted to *Operations Research.*

3. TECHNICAL REPORTS

94-6	Efficiency Improvement Techniques, April 1994	Peter W. Glynn
94-7	A Family of Regenerative Moment Identities, May 1994	James M. Calvin Peter W. Glynn
94-10	Increasing the Frequency of Regeneration for Markov Processes, August 1994	Sigrun Andradottir James M. Calvin Peter W. Glynn
94-11	Large Deviations for the Infinite Server Queue in Heavy Traffic, August 1994	Peter W. Glynn
94-12	Accelerated Regeneration for Markov Chain Simulations, September 1994	Sigrun Andradottir James M. Calvin Peter W. Glynn
94-13	A Martingale Approach to Regenerative Simulation, September 1994	Peter W. Glynn Donald L. Iglehart
94-18	Average Case Behavior of Random Search for the Maximum, December 1994	James M. Calvin Peter W. Glynn
94-19	Complexity of Non-Adaptive Optimization Algorithms for a Class of Diffusions, December 1994	James M. Calvin Peter W. Glynn
95-1	Two Approaches to the Initial Transient Problem, April 1995	Peter W. Glynn
95-2	Performance Analysis of Future Event Sets, May 1995	Halim Damerdji Peter W. Glynn
95-4	Efficient Simulation via Coupling, June 1995	Peter W. Glynn Eugene W. Wong
95-5	Some New Results on the Initial Transient Problem, June 1995	Peter W. Glynn
95-6	A Set of Extensions to the SIMAN/ARENA Simulation Environment, August 1995	Marcelo J. Torres Peter W. Glynn
96-6	Limit Theory for Performance Modeling of Future Event Set Algorithms, June 1996	Halim Damerdji Peter W. Glynn
96-7	Derandomizing Variance Estimators, June 1996	Shane Henderson

		Peter W. Glynn
96-9	Nonparametric Estimation of Tail Probabilities for the Singer Server Queue, July 1996	Peter W. Glynn Marcelo Torres
96-10	Grid-Based Simulation and the Method of Conditional Least Squares	Peter W. Glynn Kathy Ensor
96-14	Numerical Computation of Large Deviations Exponents Via Simulation	Peter W. Glynn
97-1	Simulating the Maximum of a Random Walk February 1997	Peter W. Glynn Katherine Ensor
97-2	Stochastic Optimization via Grid Search, February 1997	Peter W. Glynn Katherine Ensor
97-4	Tightness for Non-irreducible Markov Chains, June 1997	Peter W. Glynn Sean Meyn
97-5	On the Asymptotic Optimality of the SPT Rule for the Static Flow Shop Average Completion Time Problem, June 1997	Cathy J. Xia G.Shanthikumar Peter W. Glynn
97-7	Computational Efficiency Evaluation in Output Analysis, July 1997	Halim Damerdji S. Henderson Peter W. Glynn
97-10	Estimation of Continuous-Time Markov Processes Sampled at Random Time Intervals, July 1997	Darrell Duffie Peter W. Glynn

5. SCIENTIFIC PERSONNEL

The following scientific personnel were supported on this contract.

Faculty supported:

Peter W. Glynn, Professor and co-Principal Investigator

Donald L. Iglehart, Professor co-Principal Investigator

Honors

Peter W. Glynn was appointed the Thomas Ford Professor of Engineering in 1996.